

Appendix 7 Permeable Paving Research: Infiltration Performance Over Time and Maintenance Strategies

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS									
<p>Porous Asphalt</p> <p>Fwa, T.F., Tan, S.A., & Guwe, Y.K. (1999). Laboratory evaluation of clogging potential of porous asphalt mixtures (Paper No. 99-0087). In <i>Transportation Research Record: Journal of the Transportation Research Board</i>. No. 1681, pp. 43-49.</p>	Laboratory	Soil was washed into four different porous asphalt mixtures. Permeability (K) was measured after each clogging attempt until the change in permeability was negligible.	<p>Mix 1: initial K = 300.88 in/hr terminal K = 22.00 in/hr</p> <p>Mix 2: initial K = 820.22 in/hr terminal K = 457.20 in/hr</p>	Analysis utilized falling head test that increases infiltration rates; however, rates for optimum mixes far exceed any design storm infiltration need. All mixes currently used on Singapore roadways are apparently used as a topcoat application.									
<p>Wei, I.W. (1986). <i>Installation and evaluation of permeable pavement at Walden Pond State Reservation – Final report</i>. Report to the Commonwealth of Massachusetts, Division of Water Pollution Control (Research Project 77-12 & 80-22). Boston, MA: Northeastern University, Department of Civil Engineering.</p>	Field evaluation of Walden Pond State Park parking lot in Massachusetts.	Various asphalt mixes were installed in different locations in the new parking lot and evaluated for infiltration rates using sprinkler systems and collection wells.	<p>Best performing mixes:</p> <table border="1"> <tr> <td>1978</td> <td>1980</td> <td>1981</td> </tr> <tr> <td>K mix: 40 in/hr</td> <td>38 in/hr</td> <td>37 in/hr</td> </tr> <tr> <td>J3 mix: 28 in/hr</td> <td>4 in/hr</td> <td>13 in/hr</td> </tr> </table>	1978	1980	1981	K mix: 40 in/hr	38 in/hr	37 in/hr	J3 mix: 28 in/hr	4 in/hr	13 in/hr	Test plots were exposed to traffic, but not the heaviest loads in the overall parking area. No maintenance program.
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<p>St. John, M.S., & Homer, R.R. (1997). <i>Effect of road shoulder treatments on highway runoff quality and quantity</i>. Seattle, WA: Washington State Transportation Center (TRAC).</p>	Field evaluation of road shoulder treatments in Washington state.	Three types of road shoulder treatments (conventional asphalt, gravel, and porous asphalt) were installed on a heavily traveled two-lane road. Flow-weighted composite samples were collected and runoff quality and quantity was evaluated.	After one year of use the porous asphalt shoulders showed no signs of clogging and had an average infiltration rate of 1750 in/hr.	During the year of monitoring approximately 4.2 ft ³ of sand was applied per test section length for routine sanding operations. No maintenance program reported for the porous asphalt shoulders.									
<p>Cahill, Thomas, Cahill Associates. Personal communication, April, 2003.</p>	Interview Tom Cahill concerning their porous asphalt installations.	Cahill Associates has installed approximately 80 porous asphalt surfaces (mostly parking lots and recreation facilities) over the past 20 years. Visual inspections are conducted during rain events.	Visual inspections indicate no failures of any installations and Cahill estimates that oldest surfaces are functioning at 80% of initial capacity.	Cahill stresses that proper installation and strict sediment control are critical. Cahill installations use a perimeter infiltration gallery (hydrologically connected to storage under paved surface) as a backup if asphalt infiltration rate is degraded.									
<p>Hossain, M., Scofield, L.A., & Meier, W.R. (1992). Porous pavement for control of highway runoff in Arizona: Performance to date. In <i>Transportation Research Record No. 1354</i>. Transportation Research Board, National Research Council, Washington, D.C., pp. 45-54.</p>	Field evaluation near Phoenix, Arizona.	Structural integrity and permeability were evaluated for a 3,500 ft-long porous pavement test section installed on the three northbound lanes of Arizona State Route 87 near Phoenix.	<ul style="list-style-type: none"> Initial permeability (1986): 100 in/hr. After 5 years of service (1990): 28 in/hr. 	The porous asphalt has performed well in a heavy traffic (highway) application with "no cracking or significant surface deformation having occurred during the 5 years of service."									

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Permeable Pavers Borgwardt, S. (1994). <i>Expert Opinion</i> . Hannover, Germany: University of Hannover, Institute for Planning Green Spaces and for Landscape Architecture.	Field evaluation of two train station parking lots in Europe. One lot was two years old and the other five years old.	Sprinklers applied simulated rainfall on test section and measured infiltration utilizing infiltrometer (double ring method). Infiltration rates at 60 minutes are used to represent saturated conditions. Grain size distribution was evaluated to correlate paver design with infiltration rate.	<ul style="list-style-type: none"> 2-yr old lot: infiltration rate = 2.84 in/hr after 60-min sprinkling. 5-yr old lot: infiltration rate = 5.70 in/hr after 60-min. of sprinkling. 	Higher infiltration rate for the older as compared to the newer installation likely due to application of sand on top of gravel in drainage openings and fines introduced from inadequately washed aggregate base material in newer parking lot. No reported maintenance program.
Smith, D. R. (2000). <i>Permeable interlocking concrete pavements: Selection, design, construction, maintenance</i> . Washington, D.C.: Interlocking Concrete Pavement Institute.	Literature review.	Design, construction, maintenance, and infiltration capacity guidelines developed by the Institute's technical committee from literature review.	Smith recommends 1.1 in/hr infiltration rate and a CN of 65 (all soil types) for permeable interlocking concrete pavements. Infiltration rate is for a 20-year life span.	
Borgwardt, S. (1997 February). Performance and fields of application for permeable paving systems. <i>Concrete Precasting Plant and Technology</i> , pp. 100-104.	Field evaluation of various driving surfaces in Europe.	Several permeable driving surfaces of various ages were evaluated using a drip infiltrometer.	Reports a durable infiltration rate of 4.25 in/hr.	No reported maintenance programs.
Pratt, C.J., Mantle, D.G., & Schofield, P.A. (1989). Urban stormwater reduction and quality improvement through the use of permeable pavements. <i>Water Science and Technology</i> , 21, pp. 769-778.	Field evaluation of experimental plots.	A 4.6m-wide by 40m-long by 350mm-deep (on average) parking area was excavated and divided into 4 trial areas. Each trial area was filled with a different type base aggregate and water quality and quantity measurements taken from under-drains. The wearing course was cement paving blocks and plots were lined with an impermeable membrane.	<p>Three periods were measured during 30 days with a total rainfall of 80.5mm. The 350mm of various sub-base stone and pavers reduced the following amounts of the total precipitation:</p> <ul style="list-style-type: none"> Granite: 25% Limestone: 39% Blast furnace slag: 45% Gravel: 37% 	

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<p>Brattebo, B.O., Booth, D.B. (2003, November). <i>Long-term stormwater quantity and quality performance of permeable pavement systems</i>. Water Research, 37, 4368-4376.</p>	<p>Field evaluation in Puget Sound.</p>	<p>Two plastic grid systems (1 filled with soil and grass and 1 with gravel), a concrete block lattice filled with soil and grass, and concrete blocks with gravel filled cells were installed in a parking lot in the city of Renton, WA. Each stall was evaluated for infiltration capability, infiltrate water quality, and durability. Two parking stalls with each type of permeable paving material and a conventional asphalt stall, for a control, were installed in 1996.</p>	<p>Surface runoff was measured throughout Nov. 2001 and from Jan. to early March 2002. Total rainfall during the collection period was 570mm delivered in 15 distinct precipitation events. The most intense storm event delivered 121mm of rain in 72 hours. The permeable stalls infiltrated virtually all stormwater. Surface runoff occurred for 6 events (other measurable surface runoff was detected, but attributed to leaks in the system). The most significant runoff volume of the 6 events was 4mm during the largest storm noted above (3% of total precipitation).</p>	<p>The permeable parking facility was monitored for the first year following construction. This study is a follow up to that work.</p> <p>The parking stalls were used constantly during the 6 years previous to this monitoring cycle. None of the permeable paving surfaces showed signs of major wear.</p>
<p>Dierkes, C., Kuhlmann, L., Kandasamy, J., & Angelis, G. (2002, September). Pollution retention capability and maintenance of permeable pavements. In <i>"Global solutions for urban drainage". Proceedings of the Ninth International Conference on Urban Drainage</i>. Portland, OR.</p>	<p>Field evaluation.</p>	<p>The infiltration rate of a parking stall in a 15-year old permeable paver installation in a shopping center was determined. The stall was then excavated to examine contaminant levels in the underlying base aggregate and soil. Stall was selected with high content of spilled oil on surface. A drip infiltrometer was used to measure infiltration rates.</p>	<p>The paving structure consisted of: pavers with 1-3 mm joints, 5-8 cm thick bedding material (2-5 mm), and a 20-25 cm base of crushed stone (8-45 mm).</p> <p>Infiltration rate: 440 liters/second/hectare in the central region of the stall and 2000 liters/second/hectare at the edges of the stall.</p>	
<p>Clausen, J.C., & Gilbert, J.K. (2003, September). <i>Annual report: Jordan Cove urban watershed section 319 national monitoring program project</i>. Storrs-Mansfield, CT: University of Connecticut, College of Agriculture and Natural Resources.</p>	<p>Field evaluation in southeastern Connecticut.</p>	<p>Two conventional asphalt, two conventional crushed aggregate, and two permeable paver (JINI group Eco-Stone) driveways were monitored during a 12-month period for runoff, infiltration rate, and pollutant discharge. Trench drains at the bottom of the driveways with tipping buckets measured runoff volume. Infiltration rates were assessed using 2 methods: a single ring infiltrometer and a perforated hose for a flowing test. Contributing area for each driveway and land cover type (roof, lawn, etc.) was assessed.</p>	<p>Infiltration rates for the permeable pavers:</p> <ul style="list-style-type: none"> • Infiltrometer 2002: 7.7 in/hr. • Infiltrometer 2003: 6.0 in/hr. • Flowing infiltration 2003: 8.1 in/hr. • Runoff coefficient for pavers (runoff depth/rainfall depth) = 24%. 	<p>No maintenance program reported. The Eco-Stone driveways were two years old at the time of the study.</p>

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<p>Pervious Concrete</p> <p>Wingerter, R., & Paine, J.E. (1989). <i>Field performance investigation: Portland Cement Pervious Pavement</i>. Orlando, FL: Florida Concrete and Products Association.</p>	<p>Laboratory and field evaluation in Florida.</p>	<p>Test slabs of pervious concrete were poured, 18" cores removed, and infiltration rates tested. Cores were then clogged by adding 2" of sand and pressure washing for 1.5 hrs. Existing porous concrete installations were also evaluated by coring and measuring infiltration rates and percent of void space infiltrated by fines.</p>	<p>Laboratory core</p> <ul style="list-style-type: none"> • Pre-clogging infiltration rate = 23.97 in/min. • Post-clogging infiltration rate with 1" sand remaining on surface = 3.66 in/min and 10.22in/min with sand removed from surface. <p>Field tests</p> <ul style="list-style-type: none"> • Naples FL restaurant parking lot 6.5 yrs. old: infiltration rate = 4 in/min, 3.4% infiltrated by fines. • Fort Myers parking area 8 yrs. old: infiltration rate = 7 in/min, 0.16% infiltrated by fines. 	<p>Analysis utilized falling head test that increases infiltration rates, however, rates far exceed any design storm infiltration need. No reported maintenance programs.</p>
<p>Maintenance</p> <p>Balades, J.D., Legret, M., & Madiec, H. (1995). Permeable pavements: Pollution management tools. <i>Water Science and Technology</i>. 32, 49-56.</p>	<p>Field evaluation in France.</p>	<p>Various street cleaning techniques were applied to different permeable pavements, including parking lots and roads with heavy traffic. Infiltration rates measured before and after cleaning.</p>	<p>Sweeping followed by suction:</p> <ul style="list-style-type: none"> • Highly clogged surfaces (< 14 in/hr) no improvement. • Partially clogged surfaces (112–140 in/hr) original infiltration rates (210.60–224.64 in/hr) were obtained after two passes. <p>Suction only</p> <ul style="list-style-type: none"> • 1st site: initial infiltration rate = 7.02 in/hr, after two passes infiltration rate = 28.08 in/hr. • 2nd site: initial infiltration rate = 210.60 in/hr, after two passes infiltration rate = 280.80 in/hr. <p>High pressure wash with suction</p> <ul style="list-style-type: none"> • Shopping mall: initial infiltration rate = 9.83 in/hr (parking area) and 28 in/hr (roadway), after two passes infiltration rates = 84.24 in/hr for both parking and roadway. • Residential road: initial infiltration = approximately 0 in/hr, after treatment infiltration rate = 112 in/hr. 	<p>The analysis does suggest that restoring a percentage or all of the initial infiltration rate of a permeable pavement installation is possible. However, the type of permeable surface and the cleaning technique applied to that specific surface was not reported.</p>

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<p>Gerrits, C., & James, W. (2001). <i>Restoration of infiltration capacity of permeable pavers</i>. Master's thesis, University of Guelph, Guelph, Ontario, Canada.</p>	<p>Field evaluation of pervious paver (Eco-Stone) parking lot surfaces at University of Guelph in Ontario.</p>	<p>110 9m x 9m plots in the parking lot were tested for infiltration rates. Material in the drainage cells was excavated to various depths and tests repeated to evaluate regenerating infiltration capacity. Plots were categorized by low, medium and high average daily traffic, and paver bedding material. Parking lot was approximately 8 years old at time of research. Lot is sanded and plowed for snow during winter.</p>	<p>• 3" gravel bed: low traffic: initial = 5.85 in/hr excavate 20 mm = 7.8 in/hr med traffic: initial = 0.58 in/hr excavate 20 mm = 7.80 in/hr</p> <p>• 4" sand bed: low traffic: initial = 0.35 in/hr excavate 20 mm = 0.94 in/hr med traffic: initial = 0.12 in/hr excavate 20mm = no change</p>	<p>Authors find that vacuuming upper 5-20 mm of drainage cell material can regenerate infiltration, and that amounts of material removed to improve infiltration rates can be achieved by modern street sweeping equipment. Sand bed with high traffic most difficult to regenerate and medium traffic with gravel bed easiest to regenerate. Areas with pine needles and vegetation on drainage cells had higher infiltration rates than plots without vegetation material.</p>
<p>Dierkes, C., Kuhlmann, L., Kandasamy, J., & Angelis, G. (2002, September). Pollution retention capability and maintenance of permeable pavements. In "Global solutions for urban drainage"; <i>Proceedings of the Ninth International Conference on Urban Drainage</i>. Portland, OR.</p>	<p>Field evaluation.</p>	<p>A high-pressure wash and vacuum street cleaning machine was used to clean a school yard permeable paver installation (approximately 4 yr old). The pavers were 10 cm x 20 cm x 8 cm installed on a 2-5 mm pea gravel leveling layer, and the joints filled with 1-3 mm basalt aggregate. Infiltration rates before and after cleaning were evaluated using a drip infiltrometer.</p>	<p>• Infiltration rate before cleaning at 3 selected points: less than 1 mm/second/hectare. • Infiltration rates after cleaning at same 3 points: 1545-5276 liters/second/hectare.</p>	

